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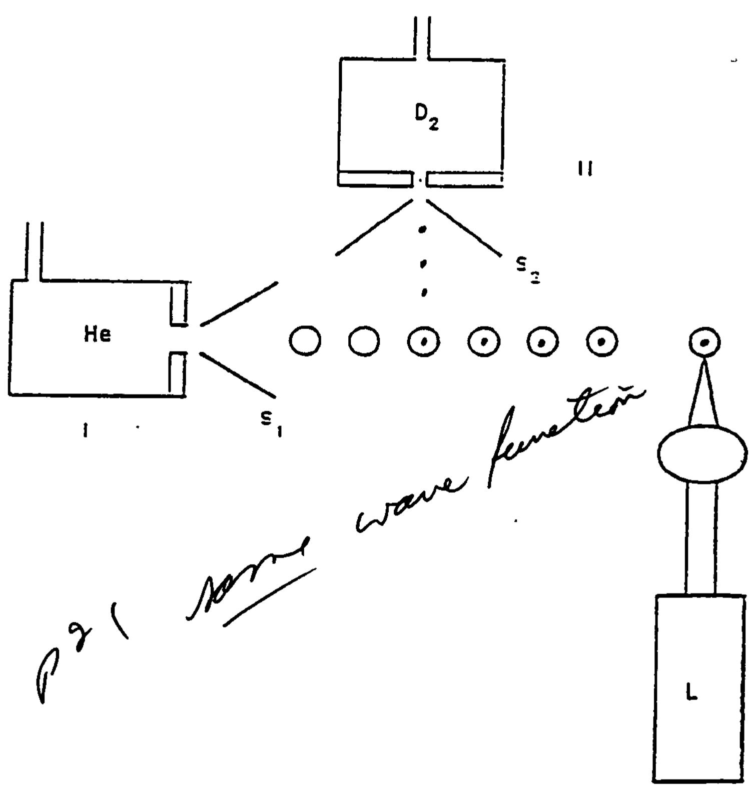
(54) Title: METHOD AND APPARATUS FOR GENERATING NUCLEAR FUSION ENERGY BY COHERENT BOSONS

(57) Abstract

With an extremely short laser pulse with not too high an intensity it is possible to ionize deuterium, or helium into coherent bosons such as coherent deuterons and coherent alpha particles. To achieve this coherence it is important that certain critical conditions are satisfied so that plasma instabilities such as stimulated Raman scattering, stimulated Brillouin scattering, parametric instability have not enough time to grow to destroy the coherence. The electrons created during the multiphoton ionization process also must not recombine with the ions or to destroy the coherence of the ions by electromagnetic scattering. With the creation of coherent deuterons and coherent alpha particles together, the fusion rate of coherent deuterons into coherent alpha particles will be greatly enhanced. The nuclear fusion energy thus released can be utilized.



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Method and Apparatus for Generating Nuclear Fusion Energy By Coherent Bosons

Background of the Prior Art

The interaction of a laser pulse and deuterium pellets have been going on for many years in connection with inertia confinement fusion schemes. For example, Lawrence Livermore Laboratory in California has a huge laser used continuously on experiments of fusion. However, the duration of the laser pulse is generally of the order of a nanosecond. In this range of time, deuterium will be ionized into plasma, and the plasma will develop instabilities. Plasma instabilities are one of the most difficult problems to confront in the fusion community. According to the present invention, a laser pulse is used which is about ten thousand times or more shorter in duration, and the intensity of the laser pulse is much smaller so that plasma instabilities do not have time to develop.

In the conventional inertia confinement scheme the idea is to increase the density of the deuterium to get the two deuterons closer and to increase the temperature to ignite the nuclear fusion. In the present invention, there is no attempt to this. Instead, utilized is the coherent effect of the bosons involved to enhance the nuclear fusion rate so that nuclear fusion can be accomplished in an extremely short duration of time. It is desired that the deuterons stay as cold as possible so that their coherence is not destroyed.

Laser pulse to ionize deuterium with one single photon per atom to initiate nuclear fusion utilizing coherent effect has been disclosed by the present inventor in U.S. Serial No. 338,706 "Enhanced Fusion Decay of Deuterium" (April 12, 1990) and is further discussed in PCT/US89/02366 and PCT/US90/01990, all incorporated herein by reference. The single photon then must have energy above 13.6 eV, which is the ionization energy of the deuterium atom. Such laser is classified as ultraviolet laser and is currently not available

commercially. The current scheme is to use a multiphoton ionization mechanism to ionize deuterium so that no ultraviolet laser is necessary. The precise conditions for multiphoton ionization has been determined.

This discussion is examined in two parts:

(I) Production of coherent bosons from multiphoton ionization.

(II) Enhancement of nuclear fusion rate among coherent bosons, with figure for apparatus.

While discussed herein is the use of superfluid deuterium, other forms of deuterium may be used. The deuterium must just be cold enough to achieve the results described. Recommended temperatures of deuterium are from liquid helium temperature to room temperature or from 1^0 to 10^0 Kelvin.

Summary of Invention

Disclosed herein is a method for creating coherent bosons such as deuterons, or alpha particles from atoms or molecules such as deuterium, deuterium compound or helium stored at a sufficiently low temperature which is to be determined by a critical condition by multiphoton ionization process.

The multiphoton ionization is initiated by a laser pulse. The energy of the laser pulses after focusing must be large enough to initiate multiphoton ionization, but must not be too large so as to heat up the plasma created, and destroy the coherence. The duration of the laser pulse must be short enough so that plasma instability does not have time to grow, and the recombination of the ions and electrons does not have time to proceed.

The method is for creating coherent bosons from superfluids by multiphoton ionization process. The coherent bosons can be coherent deuterons and coherent alpha particles, whereas the corresponding superfluids are superfluid deuterium and superfluid helium.

The method is for creating more than one kind of

coherent bosons from more than one compound at low temperature by multiphoton ionization process.

Disclosed is a method for the release of nuclear energy through the creation of coherent deuterons from deuterium, or its compound at low temperature which is to be determined by a critical condition by a multiphoton process.

Disclosed is a method for the release of nuclear energy through the creation of coherent deuterons and coherent alpha particles from deuterium or its compound with superfluid helium by a multiphoton ionization process. The coherent alpha particle induces the coherent deuterons to fuse much quicker into coherent alpha particles and coherent gamma ray with the release of nuclear energy.

The method is for creating coherent gamma ray, which is also called gamma ray laser.

Also disclosed is an apparatus for creating coherent bosons such as coherent deuterons or coherent alpha particles from atoms or molecules such as deuterium, deuterium compound or helium stored at a sufficiently low temperature which is to be determined by a critical condition by multiphoton ionization process.

The superfluid helium clusters are created by squeezing liquid helium in a cell through a nozzle from a high pressure region into a vacuum chamber. Simultaneously a deuterium cluster beam is formed by squeezing liquid deuterium in a cell through a nozzle from a high pressure region into a vacuum chamber. The two cluster beams are made to collide and merge into one compound cluster beam. A laser pulse is focused into the compound cluster to initiate nuclear fusion reactions.

In the Drawings

Figure 1 is a diagrammatic view of the invention.

Detailed Description of the Invention

I. Production of Coherent Bosons from Multiphoton Ionization

Section (1)

Introduction

There are many coherent bosons in nature, such as the Cooper pair in a superconductor, photons from laser, helium atoms in superfluid helium. There are also some investigations on coherent pions [1] in high energy hedron hadron collision. Since some of the coherent bosons such as in superconductivity and laser are particularly useful, it is interesting to investigate another system of coherent bosons. In particular, we wish to investigate the possibility of coherent deuterons or coherent α-particles. These coherent muclei may also enhance nuclear fusion.[2] In particular, we want to investigate here the production of coherent bosons from multiphoton ionization.

There are many experiments that use short pulse laser on deuterium gas or solid at cryogenic temperature. There are no coherent particles reported being produced. It is important to work out the stringent condition that coherent particles are produced, and the coherence is not destroyed immediately. When a strong laser pulse interacts with say, a coherent helium cluster, there are many possible physical processes.

(1) Multiphoton ionization. The helium atom will be ionized by multi-photons:

$$N\gamma + He \rightarrow \alpha + e^- + e^- \qquad (1.1)$$

For a strong enough pulse, it will be ionized in the first cycle 10^{-14}sec. Electrons will be emitted and form a plasma. The experimental condition is set up so that m coherent α particles are created: m coherent helium atoms:

$$n\gamma + mHe \rightarrow m\alpha + m(e^- + e^-) \qquad (1.1a)$$

(2) Stimulated Raman Scattering (SRS)

The laser pulse interacts with the plasma formed by electrons to create plasmons:

$$\gamma \rightarrow \gamma + \phi_e \qquad (1.2)$$

ϕ_e = plasmon

In laser fusion experiments, this process is known to produce fast electrons and preheat the target. For the coherent α particles which are produced from multiphoton ionization processes to remain coherent, it is important that fast electrons are not produced from SRS process to destroy the coherence.

(3) Stimulated Brillouin scattering (SBS)

The laser pulse can also interact with ions in the plasma to create phonons in the ion plasma:

$$\gamma \rightarrow \gamma + \phi_i \qquad (1.3)$$

ϕ_i = ion acoustic wave

It is preferable that this does not happen too fast.

The phonons, or ion acoustic

wave also will heat up the ions and destroy its coherence by heating.

(4) Parametric instability

The laser can also create both plasmon and ions acoustic wave in the plasma:

$$\gamma \rightarrow \phi_e + \phi_i \tag{1.4}$$

Both of these waves will heat up the plasma and could destroy coherence.

(5) Recombination

The ions α could also recombine with electrons and then we have no coherent charged ions left. The ions could recombine with electrons basically through either a two-body process:

$$\begin{aligned} &\alpha + e^- \rightarrow He^+ + \gamma \\ &He^+ + e^- \rightarrow He + \gamma \end{aligned} \tag{1.5}$$

or a three-body process.

$$\begin{aligned} &\alpha + e^- + e^- \rightarrow He^+ + e^- \\ &He^+ + e^- + e^- \rightarrow He + e^- \end{aligned} \tag{1.6}$$

We shall demonstrate that (1.5) and (1.6) are slow in a given experimental condition.

(6) The scattering between electrons and coherent α particles

Once the electrons are separated from the charged nuclei of the atoms by multiphoton ionization, they will scatter among themselves to thermalize and also scatter with the ions via Coulomb interaction. It is important that such scatterings do not destroy the coherence of the ions. The critical condition is that the electrons should not be too energetic and its density is high.

The process to diminish m coherent α particles to (m+) coherent α particles:

$$e + m\alpha \rightarrow (m-1)\alpha + \alpha + e^- \tag{1.7}$$

is to be suppressed relative to the elastic scattering

$$e + m\alpha \rightarrow m\alpha + e \tag{1.8}$$

where the coherent α particles remain to be coherent.

(7) Coherent nuclear fusion

The purpose of creating coherent charged nuclei is that they might undergo nuclear fusion to yield nuclear energy.[2]

$$m(3\alpha) \rightarrow mC + m\gamma$$

$$m(d + d) \rightarrow m\alpha + m\gamma \tag{1.9}$$

The energy from these coherent fusion reactions mainly is carried away by the high energy gamma ray indicated by $m\gamma$ above. We shall not discuss this in this paper.

All the conditions have to be found such that coherent charged nuclei are created from coherent atoms by multiphoton ionization such as (1.1a) and then they decay/fuse to release nuclear energy such as (1.9), while all the other processes (1.2 through 1.8) are either suppressed or are negligible. In the next sections, all the quantitative requirements are worked out.

Section (2)

Simple model for multiphoton ionization

Multiphoton ionization has been studied quite extensively, theoretically and experimentally.[3] The normal procedure is to use Nth order perturbation theory in quantum mechanics and the many different approaches depend upon what to use for the intermediate states. Extensive computer programs are in general needed to produce numerical results that agree with the experiment. The transition rate for N photon ionization

$$n\gamma + A \rightarrow A^{+} + (n-N)\gamma + e \tag{2.1}$$

$$A = \text{any atom}$$

is generally expressed as

$$w_N = I^N \sigma_N \tag{2.2}$$

where I is the intensity of the laser and σ_N is the generalized cross section. We notice from data (see Table 2.1) that the generalized cross section σ_N obeys simple factorization

$$\frac{\sigma_{N-1}}{\sigma_N} \sim 10^{30} \tag{2.3}$$

irrespective of what atom it is. We like to construct a simple model in quantum field theory so that this result is derived and the transition rate can be expressed in power law form as:

$$w_N = x^N \gamma. \tag{2.4}$$

$$x = I\sigma_A/\gamma_t$$

$$= \text{dimensionless quantity}$$

$I = \frac{nc}{v_\gamma}$

γ_e = decay width of excited atom A^* decaying into electron $(A^+ + e)$

σ_A = absorption cross section of photon by atom A

γ_t = width of the intermediate states

Most of the experimental results on multiphoton ionization are on absorption of two to five (N=2 to 5) photons per atom with N=11 for xeon atom. In our application, we need some order of estimate of multiphoton ionization of photon up to N=67. The above Eq. (2.4) gives us a convenient estimate of transition rate for these higher N multiphoton ionization processes.

The transition rate in Nth order perturbation theory is

$$W = \Sigma \frac{2\pi}{\hbar} \delta(E_f - E_i) |T_{fi}|^2$$

$$T_{fi} = \langle (n-N)\gamma\ e^- A^+ | H \left(\frac{1}{\Delta E} H \right)^N | A, n\gamma \rangle$$

$$= \sqrt{\frac{n!}{N!(n-N)!}} \langle e^- A^+ | H \left(\frac{1}{\Delta E} H \right)^N | A, n\gamma \rangle$$

Inserting intermediate sates A_j of the excited atom A, we have

$$T_{fi} = \sqrt{\frac{n!}{(n-N)!}} \sum \langle e^- A^+ | H | A_N \rangle \prod_{j=1}^{N} \frac{\langle A_j | H | A_j - 1, \gamma \rangle}{j(\hbar\omega - \varepsilon) - \frac{1}{2} M u_j^2 + i\hbar\gamma_j/2}$$

where

$\hbar\omega$ = photon energy

$\frac{1}{2} M u_j^2$ = kinetic energy of the atom A_j with mass M and velocity u_j

γ_j = width of the intermediate state A_j

The matrix elements are assumed to be the simplest:

$$\langle e^- A^+ | H | A_N \rangle = \frac{g_e}{\sqrt{V}} \delta_{M'\vec{u}' + m_e \vec{v}',\, M\vec{u}_N}$$

$$\langle A_j|H|A_{j-1}\gamma\rangle = ig_A \sqrt{\frac{\hbar\omega}{2V}}\, \delta_{M\vec{u}_j, M\vec{u}_{j-1}+\hbar\vec{k}}$$

$$j = 1,2\ldots.N$$

which are proportional to the coupling g_* and g_A. The kronecker deltas are there to ensure momentum conservation. The decay rate of the ionization process

$$A^* \rightarrow A^+ + e^-$$

with

$$A^* = A_N$$

is

$$\gamma_* = \frac{g_*^2 \mu_*^2}{\pi\hbar} \sqrt{\frac{2\varepsilon_*}{\mu_*}}$$

where μ^* is the reduced mass

$$\mu_* = \frac{m_e M'}{m_e + M'}$$

$$M' = m_A - m_e$$

m_A = mass of the atom

ε_* = excited energy from ground state to A_*

Let us introduce the absorption cross section

$$\gamma + A_{j+1} \rightarrow A_j$$

to be

$$\sigma_j = \frac{2g_A^2\omega}{\gamma_j \hbar c}$$

Then the transition rate is

$$W_N = \frac{\sigma_1\sigma_2\cdots\sigma_N}{\gamma_1\gamma_2\cdots\gamma_N}\,\gamma_*\,I^N$$

If we take all absorption cross sections to be the same, and all the intermediate levels have the same width

$$\sigma_1 = \sigma_2\cdots = \sigma_N = \sigma_A$$

$$\gamma_1 = \gamma_2\cdots = \gamma_N = \gamma_t$$

we obtain the Eq. (2.4) we want.

Using (2.4) with data of Table (2.1), we can estimate numerical values for σ_A/γ_t and γ_*. They are listed in Table (2.2) for various atoms.

TABLE 2.1

Experimental Values of MPI Cross Sections with Linearly Polarized Light

Atom	N	λ (nm)	σ_N min	σ_N Measured value	σ_N max	References
Cs	2	528.0	4.8×10^{-50}	6.7×10^{-50}	8.6×10^{-50}	Normand and Morellec (1980)
He*2S[1]	2	347.26	7×10^{-50}	2.7×10^{-49}	4.7×10^{-49}	Lompre et al (1980)
-- 2S[3]	2	--	10^{-50}	1.5×10^{-49}	2.9×10^{-49}	
Na	3	694.5	4.3×10^{-77}	5.4×10^{-77}	6.7×10^{-77}	Cervanen et al (1975)
K	3	--	2.8×10^{-79}	3.5×10^{-79}	4.4×10^{-79}	
Rb	3	--	1.1×10^{-77}	1.44×10^{-77}	1.97×10^{-77}	
Cs	3	--	1.1×10^{-77}	1.8×10^{-77}	2.9×10^{-77}	
He*2S[1]	3	693.7	5×10^{-80}	10^{-78}	4×10^{-77}	Bakos et al (1976)
-- 2S[1]	3	694.5	1.4×10^{-80}	3.3×10^{-80}	5.2×10^{-80}	Lompre et al. (1980)
-- 2S[3]	3	--	8×10^{-82}	3.0×10^{-81}	5.2×10^{-81}	
Cs	4	1060.0	6.3×10^{-108}	1.0×10^{-107}	1.6×10^{-107}	Arslandbekov et al (1975)
	4	1056.0	4.7×10^{-109}	7.5×10^{-109}	1.03×10^{-108}	Normand and Morellec (1980)
Na	5	1060.0	4×10^{-138}	1.26×10^{-137}	4×10^{-137}	Arslandbekov et al (1975)
Xe	11	1060.0	10^{-338}	10^{-336}	10^{-334}	Arslandbekov and Delone (1976)

+Data from J. Morellec, D. Normand, and G. Petite, Advances in Atomic and Molecular Physics. (D.R. Bates and B. Bederson) V.18, p.98-165, Academic Press, New York 1982 σ_N in unit $cm^{2N} sec^{N-1}$

TABLE 2.2

Numerical values for parameters σ_A, γ_* from fits to multiphoton ionization data in Table (2.1)

Atoms	N	$\gamma_*(sec^{-1})$	$\sigma_A \gamma_* / \gamma_t (cm^2)$
$He^* 2S^1$	2	$1.81x10^{13}$	$2.21x10^{-18}$
$He^* 2S^3$	2	$3.75x10^{14}$	$7.50x10^{18}$
Na	3	$4.79x10^{14}$	$2.31x10^{-16}$
Cs	2	$1.05x10^{14}$	$5.83x10^{-17}$

Section (3)

Classical growth rate of coherent α

In laser plasma interaction, it is customary to consider light in a laser pulse as a classical wave, and the classical wave can generate a classical coherent plasmon wave in plasma

$$\gamma \rightarrow \gamma + \phi_e$$

$$\phi_e = \text{plasmon}$$

The plasmon wave can, of course, be quantized and treated as a quantum wave. Classical treatment, however, is well investigated.[4] In multiphoton ionization of a superfluid helium to generate coherent α particles

$$n\gamma(\vec{k}) + m\text{He}(\vec{p}) \rightarrow m\alpha(\vec{p}\,') + me^{-}(\vec{q}\,') + (n-mN)\gamma \tag{3.1}$$

it is interesting to treat all participants as classical waves: the light wave in the laser pulse, the coherent helium atoms in superfluid helium, the coherent α particles created by ionization, and the electrons. The electrons are fermions, and we treat two electrons coming from the ionization of helium atoms as a quasicompound state, which can be represented by a boson field, and then treated classically. The four waves are coupled through an effective coupling g_α, which can be determined by the simple model for multiphoton ionization discussed in Section (2) The details are elaborated in Appendix A.

The effective interaction Hamiltonian density for (3.1) is

$$H = \int d^3x \; g_\alpha \; \phi_\alpha^* \phi_e^* \phi_{He} E^N + \text{h.c.} \tag{3.2}$$

where $\phi_\alpha, \phi_e, \phi_{He}$ are scalar field for α, (e^-e^-), and helium respectively, and E

is the electric field of the photon. The corresponding Lagrangian density is

$$\mathscr{L} = \frac{1}{2c^2}\dot{A}^2 - \frac{1}{2}(\nabla A)^2 + i\hbar\phi_{He}^*\dot{\phi}_{He} - \frac{\hbar^2}{2m_{He}}\nabla\phi_{He}^*\cdot\nabla\phi_{He} + \varepsilon_B\phi_{He}^*\phi_{He}$$
$$+ i\hbar\phi_\alpha^*\dot{\phi}_\alpha - \frac{\hbar^2}{2m_\alpha}\nabla\phi_\alpha^*\cdot\nabla\phi_\alpha + i\hbar\phi_e^*\dot{\phi}_e - \frac{\hbar^2}{4m_e}\nabla\phi_e^*\cdot\nabla\phi_e$$
$$-g_\alpha\left[\phi_\alpha^*\phi_e^*\phi_{He} + \phi_{He}^*\phi_\alpha\phi_e\right]E^N \tag{3.3}$$

where

$$\varepsilon_B = \varepsilon_1 + \varepsilon_2$$

is the combined binding energies of the first electrons ε_1 and the second electron ε_2 in the helium atom.

The photon field is represented by its vector field A and m_e m_{He} are the masses of the electron and the helium atom respectively. The Euler's equation can be derived as

$$\frac{1}{c^2}\ddot{A} - \nabla^2 A = -\frac{Ng_\alpha}{c}\frac{\partial}{\partial t}\left[\phi_\alpha^*\phi_e^*\phi_{He}E^{N-1} + \phi_{He}^*\phi_\alpha\phi_e E^{N-1}\right]$$
$$i\hbar\frac{\partial\phi_{He}}{\partial t} = -\frac{\hbar^2}{2m_{He}}\nabla^2\phi_{He} - \varepsilon_B\phi_{He} + g_\alpha\phi_\alpha\phi_e E^N$$
$$i\hbar\frac{\partial\phi_\alpha}{\partial t} = -\frac{\hbar^2}{2m_\alpha}\nabla^2\phi_\alpha + g_\alpha\phi_e^*\phi_{He}E^N$$
$$i\hbar\frac{\partial\phi_e}{\partial t} = -\frac{\hbar^2}{4m_e}\nabla^2\phi_e + g_\alpha\phi_\alpha^*\phi_{He}E^N \tag{3.4}$$

All the fields will now be treated classically. To solve these four differential equations simultaneously,[4] one shall treat the incoming wave A,ϕ_{He} as large parts and the outgoing wave ϕ_α, ϕ_e as small parts. Then dropping all higher order terms, Eq. (3.4) reduces to

$$\ddot{A} - c^2\nabla^2 A = 0$$

$$i\hbar\frac{\partial\phi_{He}}{\partial t} = -\frac{\hbar^2}{2m_{He}}\nabla^2\phi_{He} - \varepsilon_B\phi_{He}$$

$$i\hbar\frac{\partial\phi_\alpha}{\partial t} = -\frac{\hbar^2}{2m_\alpha}\nabla^2\phi_\alpha + g_\alpha\phi_e^*\phi_{He}E^N$$

$$i\hbar\frac{\partial\phi_e}{\partial t} = -\frac{\hbar^2}{4m_e}\nabla^2\phi_e + g_\alpha\phi_\alpha^*\phi_{He}E^N \tag{3.5}$$

If we choose the plane wave solution

$$A(x) = c\sqrt{\frac{2n\hbar}{\omega V_\gamma}} \qquad \omega = ck$$

$$E(x) = -\frac{1}{c}\dot{A}(x) = i\sqrt{\frac{n\hbar\omega}{2V_\gamma}}\left[e^{ikx}-e^{-ikx}\right] \tag{3.6}$$

and

$$\phi_{He}(x)=\sqrt{\frac{m}{V_\alpha}}\,e^{i(\vec{p}\cdot\vec{x}-Et)/\hbar} \qquad E = \frac{p^2}{2m_{He}} - \varepsilon_B \tag{3.7}$$

Then using the Fourier analysis on the wave equation, the following equation for the various fields can be derived

$$\left[E'_e - \frac{q'^2}{4m_e}\right]\phi_e(q') = g_\alpha\sqrt{\frac{m}{V_\alpha}}\left[i\sqrt{\frac{n\hbar\omega}{2V_\alpha}}\right]^N\phi_\alpha^*(N\hbar k+p-q')$$

$$\left[E'_e - \frac{p'^2}{2m_\alpha}\right]\phi_\alpha(p') = g_\alpha\sqrt{\frac{m}{V_\alpha}}\left[i\sqrt{\frac{n\hbar\omega}{2V_\gamma}}\right]^N\phi_\alpha^*(N\hbar k+p-q') \tag{3.8}$$

where

$$p' = (\vec{p}\,', iE'_\alpha/c) \qquad q'_e = (\vec{q}\,', iE'_e/c) \tag{3.9}$$

and the non-resonant terms have been ignored.

From (3.8) the dispersion relation can be derived as

$$\left[E'_\alpha - \frac{p'^2}{2m_\alpha}\right]\left[N\hbar\omega+E-E'_\alpha - \frac{1}{4m_\alpha}(N\hbar\vec{k}+\vec{p}-\vec{p}\,')^2\right] = g_\alpha^2\frac{m}{V_\alpha}\left[\frac{n\hbar\omega}{2V_\gamma}\right]^N \tag{3.10}$$

Setting

$$E'_\alpha = \frac{p'^2}{2m_\alpha} + i\hbar\gamma_{cl} \tag{3.11}$$

and using the energy-momentum conservation

$$N\hbar\vec{k} + \vec{p} = \vec{p}' + \vec{q}'$$

$$N\hbar\omega + \frac{p^2}{2m_{He}} = \frac{p'^2}{2m_\alpha} + \frac{q'^2}{4m_e} + \varepsilon_B \tag{3.12}$$

then Eq. (3.10) gives

$$\gamma_{cl} = \frac{g_\alpha}{\hbar}\sqrt{\frac{m}{V_\alpha}}\left(\frac{n\hbar\omega}{2V_\gamma}\right)^{N/2} \tag{3.13}$$

The classical coherent α wave will then grow exponentially in time as $\exp(\gamma_{cl} t)$.

Section (4)

Transition rate in quantum field model

The interaction Hamiltonian described in the last section (3.2) can, of course, be used to calculate quantum mechanically the transition rates for producing coherent α particles. The transition rate W_1 for the production of one α particle by N photon from one helium atom:

$$n\gamma + He \rightarrow \alpha + e^- + (n-N)\gamma$$

is

$$W_1 = \frac{n!}{(n-N)!}\left[\frac{\hbar\omega}{2V_\gamma}\right]^N \frac{4g_\alpha^2 m_e}{\pi\hbar^4}\sqrt{m_e(N\hbar\omega-\varepsilon_B)} \qquad (4.1)$$

For the producton of m coherent α particles from m coherent helium atom by n photons:

$$n\gamma(\vec{k})+mHe(\vec{p}) \rightarrow m\alpha(\vec{p}\,') + me^-(\vec{q}\,')+ (n-mN)\gamma(\vec{k}) \qquad (4.2)$$

the transition rate is given by m order perturbation theory to be

$$W_c = \sum \frac{2\pi}{\hbar}(E-E_i)|\langle f|H\left[\frac{1}{\Delta E}H\right]^{m-1}|i\rangle|^2 \qquad (4.3)$$

The calculation can be done easily[1] if δ-function approximation is used to approximate the propagator, and we obtain

$$\omega_c = \frac{n!\,(m!)^3}{(n-mN)!}\left[\frac{\hbar\omega}{2V_{\gamma'}}\right]^{mN}\left[\frac{\tau_1 g_\alpha}{2\hbar\sqrt{V_\alpha}}\right]^{2m-2}\frac{4g_\alpha^2 m_e}{\pi\hbar^4}\sqrt{m_e(N\hbar\omega-\varepsilon_B)}$$

where τ_1 is the interaction time for a single ionization process defined by

$$2\pi\hbar\delta(E_j-E_{j-1}) = \tau_1 \qquad (4.5)$$

The interaction time τ_m for creating m coherent α particle is τ_1/m. By uncertainty principle, we have

$$\tau_m W_c = .4 \tag{4.6}$$

Substituting this into (4.4) and solving for W_c, we get

$$W_c = 2m^2 \frac{g}{\hbar}\alpha \sqrt{\frac{m}{V_\alpha}} \left[\frac{n\hbar\omega}{2V_\gamma}\right]^{N/2} e^{-\frac{3}{2}} {-mN^2/2n} \tag{4.7}$$

For a very small m, the quantum result for transition rate for producing coherent α particles can be expressed in terms of classical results as

$$W_c \sim m^2\gamma_{cl} \tag{4.8}$$

For m $\rightarrow$ 1, the quantum result approaches the classical limit. Since m is, in general much bigger than one, the quantum transition rate is, in general, bigger than the classical result. In the last section, where numerical results are calculated, we take the conservative estimate and calculate only the classical growth rate.

In order for coherent α particles to be produced, a coherent condition has to be satisfied. This coherent condition cannot be obtained classically as is done in the last section. The classical growth rate calculation assumes automatically that the resulting α particles are in a coherent state. The quantum perturbation formalism (4.3) can be used to calculate the case where the α particles may or may not have the same momenta:

$$n\gamma(\vec{k}) + mHe(\vec{p}) \rightarrow \alpha(\vec{p}'_1) + \cdots + \alpha(\vec{p}'_m) + e^-(\vec{q}'_1) + \cdots + e^-(\vec{q}'_m) + (n-mN)\gamma(\vec{k}) \tag{4.9}$$

The transition rate is given to be

$$W_m=\sum\frac{2\pi}{\hbar}\delta(E_f-E_i)|\langle(n-mN)\gamma,e_1^-\cdots e_m^-\alpha_1\cdots\alpha_m|H\left[\frac{1}{\Delta E}H\right]^{m-1}|mHe,n\gamma\rangle|^2 \quad (4.10)$$

The result is

$$W_m=\frac{n!(m!)^2}{(n-mN)!}\left[\frac{\hbar\omega}{2V_\gamma}\right]^{mN}\left[\frac{\tau_1 g_\alpha^2 m_e}{\pi\hbar^4}\sqrt{m_e(N\hbar\omega-\varepsilon_B)}\right]^{m-1}$$

$$\frac{4m_e g_\alpha^2}{\pi\hbar^4}\sqrt{m_e(N\hbar\omega-\varepsilon_B)}\,(1+\eta)(1+2\eta)\cdots\left[1+(m-1)\eta\right] \quad (4.11)$$

where

$$1/\eta=\frac{V_\gamma}{\tau_1}\frac{4m_e}{\pi\hbar^2}\sqrt{m_e(N\hbar\omega-\varepsilon_B)} \quad (4.12)$$

The condition that all α share the same momentum state is

$$m\eta > 1 \quad (4.13)$$

so that the transition rate W_m becomes W_c of Eq. (4.7).This is similar to the condition where liquid helium becomes superfluid where the density and temperature has to satisfy the critical condition. This requires high density m/V_γ , and low kinetic momentum of the electron (or ion),,

$$p_e=\sqrt{2m_e(N\hbar\omega-\varepsilon_B)}$$

If we start off with superfluid helium where the density is high and provided the excessive energy of the N photon above the binding energy of the helium atom is not too much. If the electron has energy on the average 0.5eV, the energy of α particle is $m_e/m_\alpha\sim$ about eight thousand times smaller which is less than one degree Kelvin, so the α particles can become coherent.

Section (5)

Electron - α particle Coulomb scattering

The α particles are charged, and normally they repel one another. To have coherent α particles means that all the charged α particles have the same wave function. They pile on top of one another. This may sound surprising at first. However, in an ordinary superconductor, the cooper pair of electrons also have the same negative charge. The cooper pairs, however, can form a coherent state because the nuclei provide a neutralizing background. Here we expect the electrons emitted from the multiphoton ionization process provide the neutralizing background for the α particles to become coherent. To be sure that this actually happens, we can calculate the electron-α Coulomb scattering and see whether it can destroy the coherence.

To faciliate the calculation, we introduce the effective Hamiltonian

$$H = \int d^3 x \; g_e : \psi_e^* \Psi_e \phi_\alpha^* \phi_\alpha : \tag{5.1}$$

for the elastic Coulomb scattering

$$e^-(\vec{v}) + \alpha(\vec{u}) \rightarrow \alpha(\vec{u}') + e^-(\vec{v}') \tag{5.2}$$

where $\vec{v}$, $\vec{u}$, $\vec{v}'$, $\vec{u}'$ are the velocities of the electron and α particle before and after scattering. The Coulomb elastic cross section is

$$\sigma_e = \frac{4\pi\alpha^2}{m_e^2 \, |\vec{u}-\vec{v}|}{}_4 \ln\Lambda \tag{5.3}$$

$$\alpha = 1/137$$

where Λ is the Coulomb logarithm. By equating the cross section calculated from (5.1)

$$\sigma_e = g_e^2 m_e^2/\pi\hbar^4$$

we can determine the effective coupling g_e. The transition rate of one electron with one α particle is

$$W_1 = \frac{g_e^2 m_e^2}{\pi\hbar^4 V_\alpha}|\vec{u}-\vec{v}| \tag{5.4}$$

with the number of final state to be

$$1/\eta = \frac{V_\alpha}{\tau_1} \frac{m_e^2}{\pi\hbar^2}|\vec{u}-\vec{v}| \tag{5.5}$$

the transition rate of one electron scattering off n coherent α particles:

$$e^-(\vec{v}) + n\alpha(\vec{u}) \rightarrow (n-1)\alpha(\vec{u}') + \alpha(\vec{u}')+e^-(\vec{v}') \tag{5.6}$$

with one α particle in the final state having different velocity $\vec{u}'$ is

$$W_{1n} = nW_1 \tag{5.7}$$

In this situation the number of coherent α particles decrease by one, and the coherence will be gradually destroyed. However, one electron scatters off n coherent α particles, it is also possible that in the final state the n α particles stay coherent:

$$e^-(\vec{v}) + n\alpha(\vec{u}) \rightarrow n\alpha(\vec{u}') + e^-(\vec{v}') \tag{5.8}$$

The transition rate can also be calculated to be

$$W_{1n}^c = n^2 = n^2\eta w_1 \tag{5.9}$$

In order that coherence is not destroyed, we require the ratio of two transition rates of (5.7) and (5.9) to be bigger than 1:

$$\frac{W_{1n}^{c}}{W_{1n}} = n\eta > 1 \tag{5.10}$$

This is the same condition as that for n coherent α particles to be produced in the first place by multiphoton ionization as discussed in Sec.4 Eq. (4.13).

One can further consider the scattering of two electrons with coherent α particles:

$$e^-(\vec{v}_1)+e^-(\vec{v}_2)+n\alpha(\vec{u})\rightarrow(n-2)\alpha(\vec{u})+\alpha(\vec{u}_1')+\alpha(\vec{u}_2')+e^-(\vec{v}_1')+e^-(\vec{v}_2') \tag{5.11}$$

with the breakup of coherence. The transition rate is

$$W_{2n}=n(n-1)\left[\frac{\tau_1 g}{\hbar V_\alpha}\right]^4\frac{1}{\tau_1\eta_1\eta_2}\left[1+\frac{\pi^2}{V_\alpha}\left[\frac{\hbar}{m_e}\right]^3\frac{1}{|\vec{u}-\vec{v}_1||\vec{u}-\vec{v}_2|\vec{v}_1-\vec{v}_2|}\right] \tag{5.12}$$

where $1/\eta_1, 1/\eta_2$ are the final state numbers for the two scattered electrons

$$1/\eta_i = \frac{V}{\tau_1}\frac{m_e^2}{\pi\hbar^2}|\vec{u}-\vec{v}_i| \tag{5.13}$$

$$i = 1,2$$

For the two electrons scattering elastically off n coherent α particles:

$$e^-(\vec{v}_1)+ e^-(\vec{v}_2)+ n\alpha(\vec{u}') \rightarrow n\alpha(\vec{u}') +e^-(\vec{v}_1')+e^-(\vec{v}_2') \tag{5.14}$$

the transition rate is

$$W_{2n}^{c}= n^2(n-1)^2\left[\frac{\tau_1 g}{\hbar V_\alpha}\right]^4 \frac{1}{\tau_1} \tag{5.15}$$

The ratio of coherent transition rate W_{2n}^{c} with the incoherent transition rate W_{2n} is

$$\frac{W_{2n}^{c}}{W_{2n}} = n(n-1)\eta_1\eta_2/\left[1+\frac{\pi^2}{V_\alpha}\left[\frac{\hbar}{m_e}\right]^3\frac{1}{|\vec{u}-\vec{v}_1||\vec{u}-\vec{v}_2||\vec{v}_1-\vec{v}_2|}\right] \tag{5.16}$$

For n electrons scattering with n coherent α-particle, the ratio of coherent transition rate W^c_{nn} with the incoherent transition rate W_{nn} is

$$\frac{W^c_{2n}}{W_{nn}} = n!n_1\eta_2\cdots\eta_n \qquad (5.17)$$

where η_i are defined by (5.13). The condition for maintaining coherence is basically the same as (5.10). that of one one electron scattering off n coherent α particles.

$$n\eta > 1$$

here $1/\eta$ will be the average final state number of electrons.

Section (6)

Plasma Instability

To achieve coherence in the α particle, we require plasma instability to be negligible in the time scale (10^{-14} sec) we are considering. Plasma instability will heat up the electrons and/or the ions , and hence destroy coherence.

There are three kinds of dominant plasma instability: stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and parametric instability that occurs in the interaction between laser and plasma:

$$\text{SRS:} \quad \gamma(\vec{k}_o) \rightarrow \gamma(\vec{k}_s) + \phi_e(\vec{k}) \tag{6.1}$$

$$\text{SBS:} \quad \gamma(\vec{k}_o) \rightarrow \gamma(\vec{k}_s) + \phi_i(\vec{k}) \tag{6.2}$$

$$\text{PI:} \quad \gamma(\vec{k}_o) \rightarrow \phi_i(\vec{k}_s) + \phi_e(\vec{k}) \tag{6.3}$$

where γ, ϕ_i, ϕ_e are photon, ion accoustic wave and plasma wave. The initial momentum of the incoming photon is $\vec{k}_o$, and the two outgoing waves have moments $\vec{k}_s$ and $\vec{k}$, as indicated inside the bracket. Our concern is to investigate the classical growth rate γ_{cl} of these three instabilities[4] and study where they are much smaller than 10^{14}sec^{-1}. The normal experience in laser-plasma interaction is that within the first cycles of a strong incoming laser pulse, matter will be ionized, and many cycles later plasma instability starts to develop, probably first SRS and then SBS. The details depend very much on the strength of the pulse, the polarization, the wave length, and the structure of the plasma. Let us study them one by one.

(1) SRS - Stimulated Raman Scattering

The classical growth rate for SRS is given by

$$\gamma_{cl}^{e} = \frac{1}{4} k \, V_{os} \sqrt{\frac{\omega_{pe}}{\omega_o - \omega_{pe}}} \, |\vec{\varepsilon}_o \times \hat{k}_s| \tag{6.4}$$

where

$$V_{os} = \frac{e}{m_e c} A_o \tag{6.5}$$

$$A_o = 2c \sqrt{\frac{2\pi n \hbar}{\omega_o V_\gamma}} \tag{6.6}$$

$\vec{\varepsilon}_o$ = polarization vector of the laser

$$\omega_{pe}^2 = \frac{4\pi n_o e^2}{m_e} \tag{6.7}$$

n = number of photons in the laser pulse

V_γ = volume of the laser pulse

m_e = mass of electron

ω_o = frequency of the incoming laser pulse in vacuum

n_o = density of electrons in the plasma

The density n_o of electron in the plasma keeps increasing as the helium is being ionized. The growth rate γ_{cl}^{e} increases as $n_o^{1/4}$electron density to its one-fourth power. As the electron density increases more so that the optical frequency is smaller than the plasma frequency $\omega_o < \omega_{pe}$, the laser light cannot penetrate the plasma, there will be no more plasmon created. If we set y to be the ratio of plasma frequency to optical frequency $y = \omega_{pe}/\omega_o$, then the classical growth rate for plasmons can be expressed as

$$\gamma^{e}_{cl} = \frac{v_{os}\omega_o}{4c} f(y) \tag{6.8}$$

$$f(y) = \sqrt{2-2y-y^2+2\sqrt{(1-2y)(1-y^2)}}\ \sqrt{y/(1-y)} \tag{6.9}$$

The maximum value of f(y) occurs at

$$y = 3/8 \text{ and } f(3/8) = 1.105 \tag{6.10}$$

Let us scale the photon number n and the photon volume V_γ by

$$n = y_n \times 10^{19}$$

$$V_\gamma = y_v \times 10^{-5}\text{cm}^3 \tag{6.11}$$

we have

$$\gamma^{e}_{max} = \sqrt{\frac{y_n}{y_\gamma}}\ 1.6 \times 10^{13}/\text{sec} \tag{6.12}$$

for the case when each photon in the laser pulse has energy $\hbar\omega_o = 1.2\text{eV}$.

(2) SBS: Stimulated Brillouin Scattering:

The classical growth rate for SBS where ion acoustic wave is generated is

$$\gamma^{i}_{cl} = \gamma_o\left\{\sin\frac{\theta}{2}|\vec{\varepsilon}_o \times \hat{k}_s|\right\}^{2/3} \tag{6.13}$$

where

$$\gamma_o = \frac{\sqrt{3}}{2}\left[\frac{m_e}{M}\left(\frac{v_{os}}{c}\right)^2 y^2(1-y^2)\right]^{1/3}\omega_o \tag{6.14}$$

M = mass of the ion

θ = angle of scattered photon with the initial photon

$\vec{\varepsilon}_o$ = polarization vector of the photon.

The classical growth rate of ion acoustic wave is a function of the electron density in the plasma. When the electron clarity is small, plasma frequencyω_{pe} is small, and y is small, the classical growth rate varies as electron density to the one third power $n_e^{1/3}$. As electron density increases from ionization, it will reach a critical value when the laser cannot enter the plasma because its frequency ω_o is bigger than the plasma frequency. The ion acoustic wave will stop growing. The maximum classical growth rate occurs when $y = \sqrt{1/2}$, and we have the value to be:

$$\gamma^i = \sqrt[3]{\frac{y_n}{y_\gamma}} \text{ x } 5.88 \text{ x } 10^{12}/\text{sec} \qquad (6.15)$$

At this point, the corresponding electron density is $n_e = 5.2 \text{ x } 10^{20}/\text{cm}^3$.

(3) Parametric Excitation

The incoming light wave will excite both plasmon ϕ_e and ion acoustic wave ϕ_i

$$\gamma(\vec{k}_o) \rightarrow \phi_i(\vec{k}_s) + \phi_e(\vec{k}) \qquad (6.16)$$

We are interested in the strong coupling case where the growth rate is large compared with the frequency of the acoustic ion wave ($\gamma_{ei}^{ie} >> \omega_i$). For the strong coupling case, according to one well established way,[4] it can be calculated to give

$$\gamma_{ei}^{ie} = \frac{\sqrt{3}}{4}\left[\frac{m_e}{M}\left(\frac{V_{os}}{V_e}\right)^2 (ck_o)^2 \omega_o (\vec{\varepsilon}_o \cdot \hat{k})^2\right]^{1/3} \qquad (6.17)$$

where we have

$$\omega_o = \sqrt{c^2 k_o^2 + \omega_{pe}^2} \qquad (6.18)$$

$$\omega_s = c_s k_s$$

$$v_e = \frac{5}{3}\frac{k_B T_e}{m_e}$$

T_e = temperature of the electron

M = mass of ion

$\vec{\varepsilon}$ = polarization vector of incoming light

$\hat{k} = \vec{k}/k$

$$\omega_{ek} = \sqrt{v_e^2 k^2 + \omega_{pe}^2}$$

The growth rate γ_{cl}^{ie} is also a function of electron density in the plasma. We take the maximum value:

$$\gamma_{cl}^{ie} = \frac{\sqrt{3}}{4}\left[\frac{m_e}{M}\left(\frac{v_{os}}{v_e}\right)^2\right]^{1/3}\omega_o \qquad (6.19)$$

Substituting the same scale variables as in (6.11), and take $\hbar\omega_o = 1.2\text{eV}$, we have numerically

$$\gamma_{max}^{ie} = \sqrt[3]{\frac{y_n}{y_\gamma}}\; 4.04 \times 10^{14}/\text{sec} \qquad (6.20)$$

Section 7

Recombination - Langevin's theory

The ions, once created by multiphoton ionization process, may recombine with electrons. If the recombination rate is faster than the rate of creating ions, we have no ions left. One of the final requirements then that coherent ions are possible is that the recombination rate is slow.

For low density electron $10^9/cm^3 \geq$, the theory of recombination is well studied both theoretically and experimentally[4]Bates et al call the dominant process a collisional-radiative process. The collisional part is the three body collision e^--e^--He^+ basically based on J.J. Thomson's theory. However at very high electron density which is about $10^{22}/cm^3$ in our case, the Thomson's theory does not apply, and there is very little experimental work. The relevant theoretical framework is due to Langevin. The Langevin theory[6] gives the recombination coefficient as

$$\alpha = 4\pi z e^2(\mu_e+\mu_i)$$

where z = charge of the ion, and μ_e, μ_i are the mobility of the electron and ion respectively given by

$$\mu_e = \frac{t_e}{m_e}$$

$$\mu_i = t_i/m_i$$

t_e = collision time of the electron

t_i = collision time of the ion

m_e = mass of electron

m_i = mass of the ion

The collision times are given respectively as

$$t_e = \frac{3}{4z^2e^4}\sqrt{\frac{m_e}{2\pi}}\frac{(kT_e)^{3/2}}{n_e \ln\Lambda}$$

$$t_i = \frac{3}{4z^2e^4}\sqrt{\frac{m_i}{\pi}}\frac{(kT_i)^{3/2}}{n_i \ln\Lambda}$$

Since the temperature ion is low and the electron temperature is much higher, $T_o \to o$, $(T_i << T_e)$, we have $\mu_e > \mu_i$ the electron term dominates and we have

$$\alpha = \frac{3}{ze^2}\sqrt{\frac{\pi}{2m_e}}\frac{(kT_e)^{3/2}}{n_e \ln\Lambda}$$

The pressure of the electron gas $p_e = n_e kT_e$ can also be estimated. If we take $T_e = 0.53\text{eV}$, $n_e = 4.4\text{x}10^{22}/\text{cm}^3$, we have recombination coefficient α and the recombination rate $\gamma = \alpha n_e$ for the two processes: (I) electron recombines with doubly charged ion and (II) with single charged ion:

(I) $e + H_e^{++} + e \to He^{+} + e$

(II) $e + H_e^{+} + e \to He + e$

to be

	$\gamma_R(\text{sec}^{-1})$	$\alpha(\text{cm}^3/\text{sec})$	$p_e(\text{atm})$
(I)	$1.1\text{x}10^{14}/\ln\wedge$	$4.85\text{x}10^{-9}/\ln\Lambda$	$3.7\text{x}10^4$
(II))	$1.43\text{x}10^{14}/\ln\wedge$	$6.49\text{x}10^{-9}/\ln\wedge$	$1.4\text{x}10^4$

where $\ln\wedge$ is the logarithim Coulomb cut-off term and is in the range of 2 to 10, and γ_R is the recombination rate given by $n_e\alpha$.

Section 8

Some numerical estimates

We collect all our numerical estimates from the above section for comparison as follows:

The classical growth rate for multiphoton ionization of helium:

$$\gamma_{cl}^{N} = \left[\frac{y_n}{y_V}\beta\right]^{N/2} x\ 10^{14}/\sec$$

with the constant β given by

$$\beta = 1.175x10^3 \quad (He^{*}2S^{1})$$

$$= 2.0x10^2 \quad (He^{*}2S^{3})$$

from experiments on ionizing excited helium atom from single ($He^{*}2S^{1}$) state or triplet ($He^{*}2S^{3}$) state. We shall use the β value for singlet state in our later discussion.

The classical growth for creating plasmons (SRS) is

$$\gamma_{cl}^{e} = \sqrt{\frac{y_n}{y_V}}\ 1.6x10^{13}/\sec$$

that for creating ionic acoustic wave (SBS) is

$$\gamma_{cl}^{i} = \sqrt{\frac{y_n}{y_V}}\ 6.4x10^{13}/\sec$$

and that for creating plasmons and ion acoustic wave is

$$\gamma_{cl}^{ei} = \sqrt[3]{y_n/\gamma_\gamma} \qquad 4.04x10^{14}/\sec$$

The recombination rate is

$$\gamma_R = 1.4x10^{14}/Ln\Lambda$$

$$\ln\Lambda \simeq 10$$

In order to produce a coherent α particle, we require the growth rate of the coherent α particle to be much larger than all the other growth rates:

$$\gamma_{cl}^{N} > \gamma_{cl}^{a}, \quad a = e, i, ei$$

$$\gamma_{cl}^{N} > \gamma_{R}$$

This is not difficult to achieve. For multiphoton ionization to occur in any significant rate, we have

$$\frac{y_n}{y_V}\beta = 1 + \varepsilon \, , \; \varepsilon > o.$$

Since it is raised to N/2 power, a small increase in the intensity will ensure that multiphoton ionization overwhelms all the others. For example, if we have $y_n \, y_V \sim 10^{-3}$ with $\varepsilon = 0.14$, $N = 67$, $\gamma_{cl}^{N} \sim 10^{16}$/sec.. then all the plasma instability is suppressed by a factor of at least 10, so that the growth rate is 10^{13}/sec or less. The cleanest way is to have a laser pulse with pulse duration $\tau = 10^{-14}$/sec, $\hbar\omega = 1.2$eV, focused on $10\text{x}10\mu\text{m}^2$, so that $y_V = 10^{-5}$. Then we have the total energy of the laser pulse $y_n = 10^{-8}$ or $n=10^{11}$, which is about 20 nJ. If the laser pulse duration increases to $\tau=10^{-13}$sec, we need the energy of the laser pulse increased to 200nJ. This is quite close to what can be achieved at the present state of the art. It is important to realize that we also do not want to have excessive energetic laser pulse because at a higher power rate, ionization will come from a different mechanism of electron tunneling through the potential barrier[(7)] and the ratio does not increase as power of N/2. The plasma instability will increase rapidly also. If we ever heat up either the electrons or ions by whatever mechanism, the coherence of α particles will be lost.

Appendix: Determination of the effective coupling in the multiphoton ionization of helium atom

In order to evaluate numerically the growth rate of coherent α, it is necessary that we have some estimate of the value of the effective coupling g_{α}, as defined in the Hamiltonian Eq. (3.2). The ionization of helium atom to become α particle requires the ionization of two electrons so the process is slightly more complicated. Let us first consider a simpler case of the ionization only one electron from some atom A and try to determine the effective coupling of multiphoton ionization of A:

$$n\gamma(\vec{k}) + A(\vec{p}) \to A^{+}(\vec{p}\,') + e^{-}(\vec{q}\,') + (n-N)\gamma(\vec{k})$$

As we discuss in Section (2), the transition rate is

$$W_N = x\, N\gamma. \tag{A.1}$$

with $$x = \frac{n\,c}{V_{\gamma}} \frac{\sigma_A}{\gamma_t} \tag{A.2}$$

If we use the effective Hamiltonian

$$H = \int d^3x (g_{eff} \bar{\psi}_e \psi_A \phi_A^{*} + E^N + \text{h.c.}) \tag{A.3}$$

the multiphoton ionization can be calcualted in first order perturbation theory. The transition rate is easily evaluated to be

$$W_N = \frac{n!}{(n-N)!} \left[\frac{\hbar\omega}{2V_{\gamma}}\right]^N \frac{g_{eff}^2 m_e}{\pi h^4} \sqrt{2m_e(N\hbar\omega - \varepsilon_B)} \tag{A.4}$$

Equating (A.4) with (A.1), we obtain the effective coupling to be

$$g_{eff} = \left[\frac{2g_A}{\hbar\gamma t}\right]^N g_* \tag{A.5}$$

which are in terms of parameters g_A, g_*, γ_t that are quantities genuinely in first order electromagnetic intereaction.

Next, let us consider the ionization of two electrons

$$n\gamma(\vec{k})+He(\vec{p})\rightarrow\alpha(\vec{p}')+e^-(\vec{p}_1)+e^-(\vec{p}_2)+(n-N)\gamma(\vec{k}) \tag{A.6}$$

The two electrons are fermions while all other particles are bosons, The simplest effective Hamiltonian is

$$H = \int d^3x(ig\psi_e^+\sigma_2\psi_e^*\phi_\alpha^*\phi_{He}E^N + h.c.) \tag{A.7}$$

The transition rate is

$$W_{2e} = \frac{n!}{(n-N)!}\left[\frac{\hbar\omega}{2V_\gamma}\right]^N \frac{g^2 m_e^3}{2\pi^2\hbar^7}(N\hbar\omega-\varepsilon_B)^2 \tag{A.8}$$

While retaining the fermioni character of electrons do no impede our quantum mechanical results as we just show, it is nearly impossible to use the Hamiltonian (A.7), which contains fermionic electrons, to calculate classically. There is no classical analog of fermionic wave. The only way that we proceed along the classical treatment is to treat electrons as bosons as is done often in elementary quantum mechanical problems where the spin of electrons is neglected. In problems where the spin of electron does not play an important role such as in the multiphoton ionization case, the results should be approximately correct. The simplest Hamitonian we can construct for scalar electrons for two electrons ionization process

$$n\gamma(\vec{k})+He(\vec{p})\rightarrow\alpha(\vec{p}\,')+e^{-}(\vec{q}\,')+(n-N)\gamma(\vec{k}) \quad (A.9)$$

is

$$H = \int d^3x(g_\alpha \phi_\alpha^* \phi_e^* \phi_{He} E^N + \text{h.c.}) \quad (A.10)$$

The two electrons are both scalar. We may treat them together as one boson field ϕ_e, where its momentum $\vec{q}\,'$ is the sum of momenta of the two electrons. The individual momentum of each electron is lost in this treatment. This may make one think we have underestimated the phase space of the final states in using (A.16) to calculate the transition rate. However, since it is only an effective Hamiltonian, any underestimation in the phase space will in included in the determination of the effective coupling. The transition rate from (A.10) is given in terms of effective coupling by:

$$W_e = \frac{n!}{(n-N)!}\left[\frac{\hbar\omega}{2V_\gamma}\right]^N \frac{4g_\alpha^2 m_e}{\pi\hbar^4}\sqrt{m_e(N\hbar\omega-\varepsilon_B)} \quad (A.11)$$

and the total number of states in the final state is

$$1/\eta = \frac{4m_e V}{\pi\hbar^2\tau}\alpha\sqrt{m_e(N\hbar\omega-\varepsilon_B)} \quad (A.12)$$

where τ is the interaction time.

Let us now determine the ionization rate of helium into two electrons and α using the model that we discuss in Section (2):

$$n\gamma(\vec{k})+He(\vec{p})\rightarrow\alpha(\vec{p}\,')+e^{-}(\vec{p}_1)+e^{-}(\vec{p}_2)+(n-N)\gamma(\vec{k}) \quad (A.13)$$

by a two-step model:

$$N_1\gamma + He \rightarrow He^{+} + e^{-} \quad (A.14)$$

$$N_2\gamma + He^{+} \rightarrow \alpha + e^{-} \quad (A.15)$$

The helium atom first absorbs N_1 photon to become ionized into positively singly charged helium He^+ and an electron. Then the singly charged helium He^+ absorbs another N_2 photon to become doubly charged α particle and an additional electron. The effective Hamiltonian for these two step processes is

$$H = \int d^3x(g_1\psi^*_{He}+\psi^*_e\phi_{He}E^{N_1}+ g_2\psi^*_e\psi_{He}+\phi_\alpha E^{N_2}+ \text{h.c.}) \tag{A.16}$$

These effective couplings g_1 and g_2 are determined via the method discussed in the beginning of this appendix to be

$$g_1 = \left[\frac{2g_A}{\hbar\gamma_t}\right]^{N_1} g_* \tag{A.17}$$

$$g_2 = \left[\frac{2g_A}{\hbar\gamma_t}\right]^{N_2} g_* \tag{A.18}$$

Therefore the transition rate of multiphoton ionization of helium atom into two electrons and one α particle, as in (A.13), is given by

$$W_{N_1N_2} = \frac{n!}{(n-N)!}\left[\frac{c\sigma_A}{V_\gamma\gamma_t}\right]^N \frac{g_*^{\,4}m_e^{\,3}}{\pi^2\hbar^8\gamma}\sqrt{(N_1\hbar\omega-\varepsilon_1)(N_2\hbar\omega-\varepsilon_2)} \tag{A.19}$$

where

$$\begin{aligned} N &= N_1 + N_2 \\ \varepsilon_1 &= \text{ionization energy of the first electron} \\ \varepsilon_2 &= \text{ionization energy of the second electron} \end{aligned} \tag{A.20}$$

The two square roots at the end of the (A.19) reflect the momentum integration of the two electrons phase space in the final state sum. Hence in transition rate $W_{N_1N_2}$ the phase space of two electrons are properly accounted for. We equate (A.19) with (A.11), we get the value of effective coupling g_α to be

$$g_\alpha^2 = \left[\frac{2g_A}{\hbar\gamma_t}\right]^{2N} g_*^2 \, \frac{\overline{\gamma_*}}{\gamma} \tag{A.21}$$

where

$$\overline{\gamma_*} = \frac{g_*^2 m_e}{8\pi\hbar^4}\sqrt{\frac{m_e(N_1\hbar\omega - \varepsilon_1)(N_2\hbar\omega-\varepsilon_2)}{N\hbar\omega - \varepsilon_B}} \tag{A.22}$$

So it is clear from the above that the effective coupling g_α contains information of each electron because of the excessive energies carried by each electron $N_1\hbar\omega-\varepsilon_1$, and $N_2\hbar\omega-\varepsilon_2$ are explicitly contained in (A.22). Therefore there is reason to believe that a quasi-bound two electron Hamiltonian used in Section (3) may indeed contain all the important aspects of multiphoton ionization of a helium atom.

The numerical values of various constants can be evaluated in the following way. We use the values of γ_* from Table (2.2) to calculate g_* from the relation of the decay width with its coupling constant.

$$\gamma_* = \frac{g_*^2 m_e}{\pi\hbar^4}\sqrt{2m_e(N_1\hbar\omega-\varepsilon_1)} \tag{A.23}$$

Set $N_1 = 21$, $\hbar\omega = 1.2\text{eV}$, $\varepsilon_1 = 24.588\text{eV}$, we get

$$\frac{g_*}{\hbar c}(\sqrt{\text{cm}}) = 4.30\text{x}10^{-8} \quad (\text{He}^*2\text{S}^1)$$
$$= 1.92\text{x}10^{-7} \quad (\text{He}2\text{S}^3)$$

Using these values of g_*, one calculates γ_* from (A.23), and substitutes its value into (A.21); one gets the coupling constant g_α to be

$$g_\alpha = (6\text{x}10^{-19})\text{cm}^3/\text{eV})^{N/2} \text{ x } 2.2\text{x}10^{-13}\text{cm}^{3/2}\text{eV} \qquad (\text{He}^*2\text{S}^1)$$

$$= (1\text{x}20^{-19}\text{cm}^3/\text{eV})^{N/2} \text{ x } 9.58 \text{ x } 10^{-13}\text{cm}^{3/2}\text{eV} \qquad (\text{He}^*2\text{S}^3)$$

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II. Enhancement of Nuclear Fusion Rate From Coherent Bosons.

Figure 1 is a diagrammatic view of an apparatus which may be used with substances to create enhanced nuclear fusion.

Coherent helium cluster beam, indicated by open circles o is created at I by pressurizing superfluid helium through a nozzle with a diameter $D_1 \cong 2\mu m$ into vacuum. Coherent deuterium cluster beam is created at II by pressurizing liquid deuterium through a nozzle with a diameter $D_2 = 1\mu m$ into vacuum chamber indicated by solid circle •. The two beams merge to form one beam which is then exposed to an ultra short laser pulse(L). All the particles in the cluster will be ionized to become coherent deuterons and α particles. The coherent deuterons then fuse to release nuclear energy. S1 and S2 are skimmers.

The fusion rate of two deuterons:

$$d + d \rightarrow p + He,\ n + t \tag{1}$$

is decreased exponentially by the Coulomb barrier exp(-G) with

$$G = \pi \sqrt{(2\alpha\, m_d\, a)}$$

$$\alpha = 1/137$$

$$m_d = \text{mass of deuteron} \tag{2}$$

a = distance of two deuteron at classical turning point

The central question so far in controlled fusion is to increase the fusion rate by decreasing a either through higher temperature or higher density, or both. In this paper we discuss an alternative approach of increasing fusion rate by collective effect of coherence. It is well-known in the stimulated emission processes of laser and baser[1] the transition rate of a given process can be greatly enhanced by the coherence of bosons involved. It is possible to apply this coherent enhancement factor to nuclear fusion. In particular we consider the fusion rate of two deuterons into α particle and photon

$$d + d \rightarrow \alpha + \gamma \tag{3}$$

where the final particles are also bosons. Normally (3) is down by a factor of α (=1/137) from (2) due to its electromagnetic nature. However the coherence of bosons in the final state will increase the rate[2] for the electromagnetic process (3) far larger than that of (1).

The enhancement factor can be calculated in two different ways: first by classical wave approximation, and then by quantum mechanical

calculation. The enhancement can be further increased by the existence of additional α particle in the initial state. Let us discuss them one by one:

(a) Growth rate from classical wave approximation:

Let us take the results from our previous work[2] that coherent deuterons can be created from coherent deuterium by multiphoton process. Then the fusion reaction is that among coherent bosons:

$$2nd(k_0) \rightarrow n\alpha(p) + n\,\gamma(k) + 23.8\text{MeV}$$

where k_0, p, k are the momenta of the deuteron, α particle and photon. The phenomenological interaction Lagrangian among these particles is

$$L_I = -g(\phi^*_\alpha \phi_d^2 A) \qquad (4)$$

where ϕ_α, ϕ_d, A are scalar fields for α particle, deuteron and photon, and g is the effective coupling. From variational principle we can get a set of Langrange equations for these fields:

$$\begin{aligned} i\hbar\partial\phi_d/\partial t &= -\hbar^2\nabla^2\phi_d/2m_d + 2g\,\phi_d^*\,\phi_\alpha\,A \\ i\hbar\partial\phi_d/\partial t &= -\hbar^2\nabla^2\phi_\alpha/2m_\alpha - \delta m\,c^2\,\phi_\alpha + g\,\phi_d^2\,A \\ \ddot{A} - c^2\nabla^2 A &= -gc^2[\phi_\alpha^*\,\phi_d^2 + \phi_d^{*2}\,\phi_\alpha] \\ \delta m &= 2m_d - m_\alpha = 23.85\text{ MeV} \end{aligned} \qquad (5)$$

Using the technique that is well developed from the study of instabilities in laser-plasma interaction[3], these equations can be solved easily. First, the incoming deuteron is taken to be a classical plane wave:

$$\phi_d(x) = \phi_0 \exp(-\ ik_0.x - i\omega_0 t) \qquad (6)$$

and the outgoing electromagnetic wave and α particle are expanded into fourier components :

$$A(x) = \int d^4k\, e^{ikx}\,\tilde{A}(k)$$

$$\phi_\alpha(x) = \int d^4k\, e^{ikx}\, \tilde{\phi}_\alpha(k) \tag{7}$$

where k = (k, ω) is the four vector. The frequency of the electromagnetic wave has a real part ck and an imaginary part γ_{cl}

$$\omega = ck + i\gamma_{cl} \tag{8}$$

which we identified as the classical growth rate. Substituting (6) - (8) into (5) the classical growth rate for the resonant solution is found to be

$$\gamma_{cl} = ng/V \sqrt{(2/\delta m)} \tag{9}$$

where V is the normalization volume. The coupling g can be estimated from the transition rate of (3) by using (4)

$$\Gamma_1 = g^2 \delta mc/V\pi\hbar^2 \tag{10}$$

The transition rate Γ_1 is proportional to the Coulomb barrier factor exp(-G), and in general very small. The enhancement of nuclear fusion rate due to classical wave treatment is

$$\gamma_{cl}/\Gamma_1 = n\,(2\pi\hbar^2/\delta m^2 c\ V\ \Gamma_1)^{1/2} \tag{11}$$

If Γ_1 is 10^{-70} sec^{-1}, V = 1 μm^3, n = 2.2×10^{10}, the enhancement factor is quite considerable. The ratio γ_{cl}/Γ_1 is 8.0×10^{44}.

(b) Quantum mechanical enhancement:

The transition rate of (3) can be evaluated explicitly in quantum mechanics by the usual perturbation theory(1) to be:

$$\Gamma_n = \frac{2\pi}{\hbar}\, \delta(E_f - E_i) \sum |< n\gamma, n\alpha|\ H\ (1/\Delta E\ H)^{n-1}\ |\ 2nd>|^2 \tag{12}$$

We use the approximation for the δ-function to be

$$2\pi\ \delta(0) = \int dt\ e^{i\omega t} = \tau$$

where τ is the interaction time. Then the transition rate for 2n coherent deuterons to fuse into n coherent α particles and n coherent gamma ray is

$$\Gamma_n = 1/2\ (2n)!\ (n!)^2 [\ gcn\tau/2V\sqrt{(2\hbar ck)}]^{2n-2}\ \Gamma_1 \tag{14}$$

The enhancement factor $(n!)^2$ (2n)! comes from the coherent states of $n\gamma$, $n\alpha$, and 2nd respectively. The value of Γ_n rapidly increases as n increases but its increase must be bound by the uncertainty relation $\Gamma_n\tau = 4$ which can be used to evaluate (14). Then we have

$$\Gamma_n = n^2 \gamma_{cl}(2/e^2) \qquad (15)$$

The factor $2/e^2$ comes from the use of Sterling formula to approximate the factorial $n! = (n/e)^n$. For very weak field or $n \to 1$, the above quantum mechanical result for the transition rate approached the classical growth rate γ_{cl}. For large n there is a multiplicative enhancement factor n^2 for the quantum mechanical result over the classical growth rate. For $n=10^{10}$ the multiplicative enhancement factor is 10^{20}.

(c) The nuclear fusion rate can further be increased by providing a set of coherent α particle in the initial state. This is similar to the induced transition in laser process. the reaction we want to study has coherent deuterons and coherent α together in the initial state:

$$2nd(k_o) + n_1\alpha(p) \to (n + n_1)\ \alpha(p) + n\ \gamma(k) \qquad (16)$$

The existence of coherent α particles in the beginning induces the coherent deuterons to fuse into α much more readily.The quantum mechanical transition rate for the above process (16) can be calculated in similar way:

$$\Gamma_{n,n_1} = (2n)!n!(n+n_1)![gcn\tau/2V\sqrt{(2\hbar ck)}]^{2n-2}\ \Gamma_1 \qquad (17)$$

Again using Sterling formula and uncertainty relation the enhancement factor can be evaluated to be

$$\Gamma_{n,n_1} / \Gamma_n = (1 + n_1/ n)\ (n+n_1)^{n_1/n} \qquad (18)$$

If $n_1 = 10^{11}$, and $n = 10^{10}$, the enhancement factor of having coherent α

particles in the initial state over having no coherent α particles is about n_1^{10}, which is 10^{110}, a large enough factor to overshadow the effect of Coulomb barrier.

To realize this experimentally one can sketch briefly an experiment of the following kind. As shown in Fig.(1) we can create coherent helium clusters by pressurizing superfluid helium through a nozzle with diameter $D_1 = 2\mu m$ so as to create droplets of size of similar size.[4] Superfluid D_2 clusters can also be obtained by pressurizing liquid deuterium through a nozzle to the vacuum region. Due to the rapid cooling of evaporation the temperature of liquid deuterium drops and becomes super cooled to form superfluid deuterium[5]. These two kinds of coherent clusters can be made to collide and the superfluid deuterium cluster will immerse inside the superfluid helium clusters[6]. An ultra short laser pulse of the order 10 fs and energy of μJ range is used to ionize the composite superfluid clusters. The laser pulse must be short enough so that plasma instability will not develop to destroy the coherence of the deuterons and α particles. The intensity of the laser pulse should be high enough to initial multiphoton ionization. The energy of the pulse must be just enough to ionize all the atoms and molecules but not much energy is left over to heat up the plasma[7].Normally for a strong focused laser pulse on a small object ionization is completed in the first cycle of the wave or about 10^{-14} sec. So in 10 fermto-second the superfluid helium and superfluid deuterium will be ionized to form coherent deuterium and α particles. All the plasma instabilities that we study in association with present available laser has a growth rate smaller than $10^{13}sec^{-1}$, and hence do not have time to develop. Due to the presence of

coherent α particles the coherent deuterons will almost immediately fuse to form coherent α and coherent photons with the release of nuclear energy that we so eagerly seek after.

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Claims

1. A method for creating coherent bosons from atoms stored at a temperature determined by a critical condition of a multiphoton ionization process.

2. A method for creating coherent bosons with mass from molecules stored at a temperature determined by a critical condition of a multiphoton ionization process.

3. The method of any one of claims 1 or 2 wherein said bosons are one of deuterons or alpha particles and wherein said atoms or molecules are one of deuterium, deuterium compound or helium.

4. The method of any one of the preceding claims wherein the multiphoton ionization process is initiated by a laser pulse, the energy of the laser pulses after focusing being large enough to initiate multiphoton ionization, but not too large so as to heat up the plasma created, and destroy the coherence in the plasma.

5. The method of claim 4 wherein the duration of the laser pulse must be short enough so that plasma instability does not have time to grow, and the recombination of the ions and electrons does not have time to proceed.

6. A method for creating coherent bosons from superfluids by using a multiphoton ionization process.

7. The method of claim 6 wherein the coherent bosons are one of coherent deuterons or coherent alpha particles and wherein the superfluids are one of superfluid deuterium or superfluid helium.

8. A method for creating more than one kind of coherent bosons

by use of

a) more than one compound at low temperature and

b) by multiphoton ionization process.

9. A method for the release of nuclear energy through the creation of coherent deuterons from deuterium, or its compounds, at low temperature which is to be determined by a critical condition by a multiphoton process.

10. A method for the release of nuclear energy through the creation of coherent deuterons and coherent alpha particles from deuterium or its compounds with superfluid helium by a multiphoton ionization process, the coherent alpha particle inducing the coherent deuterons to fuse into coherent alpha particles and coherent gamma rays with the release of nuclear energy, said method creating coherent gamma rays, which is also called a gamma ray laser.

11. A method for creating coherent bosons such as coherent deuterons or coherent alpha particles from atoms or molecules such as deuterium, deuterium compound or helium stored at a sufficiently low temperature which is to be determined by a critical condition by multiphoton ionization process said method involving the steps of

squeezing liquid helium through a nozzle from a high pressure region into a vacuum chamber thereby creating a beam of superfluid helium clusters;

forming a deuterium cluster beam by squeezing liquid deuterium through a nozzle from a high pressure region into a vacuum chamber;

causing said two beams to collide wherein said two beams become a single compound cluster beam;

focusing a laser pulse into the compound cluster beam to initiate nuclear fusion reactions.

12. An apparatus for creating coherent bosons from atoms or molecules stored at a sufficiently low temperature that is determined by a critical condition by multiphoton ionization process said apparatus comprising:

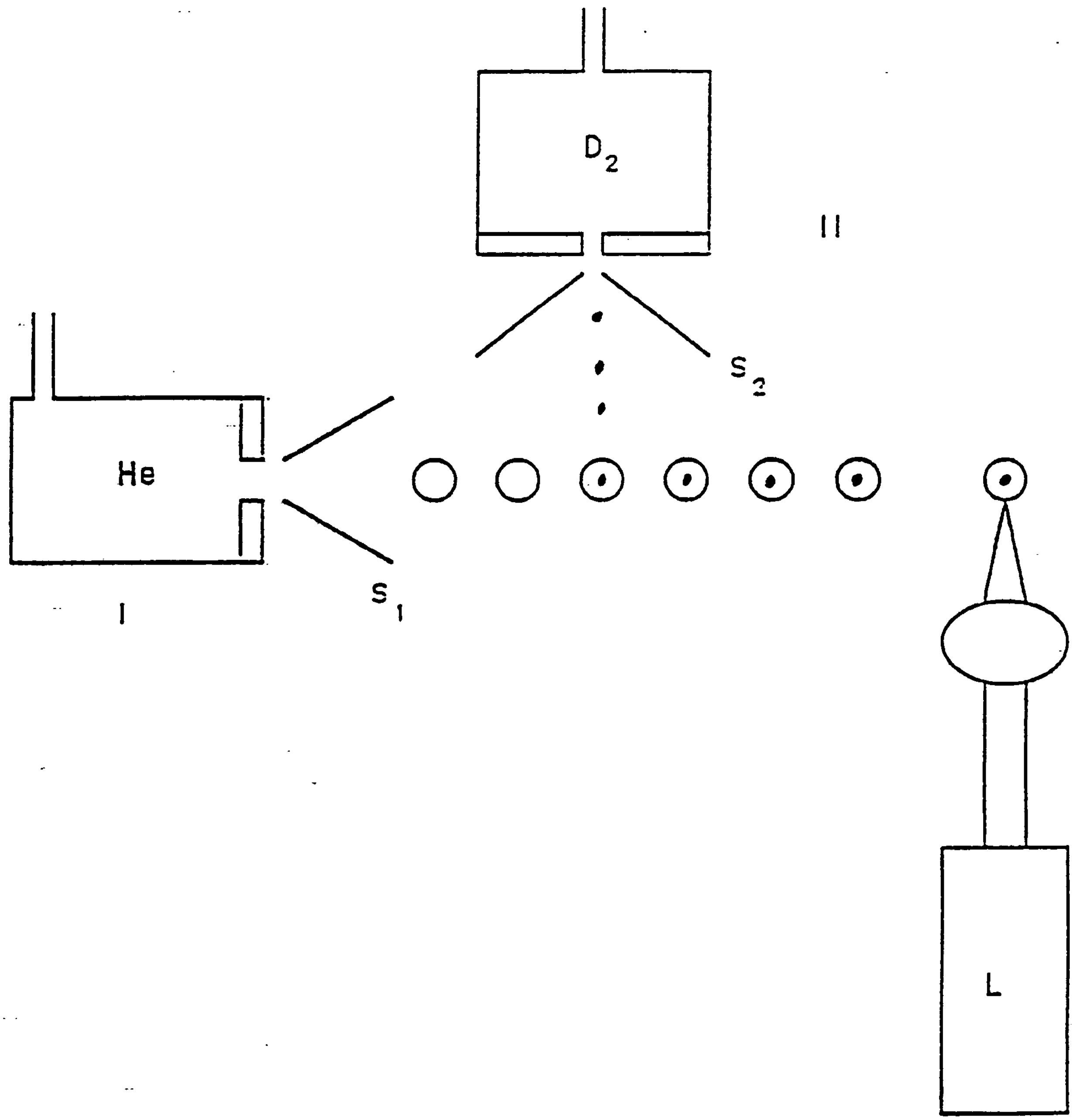
a first chamber held at a first pressure;

a second chamber held at a second pressure that is lower than said first pressure,

means for passing a substance from said first chamber into said second chamber;

a laser means for directing a laser beam on said substance after it has passed into said second chamber and collided with another substance which has been passed from a first higher pressure to a second lower pressure.

FIG. 1



INTERNATIONAL SEARCH REPORT

International Application No.
PCT/US92/10361

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G21B 1/00
US CL :376/100
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 376/100 376/120,122; 250/251,423R,423P,424; 372/39

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US,A, 4,875,213 (Lo) 17 October 1989 See col. 2, lines 37+, col. 4, line 28+.	1-10 11,12
X Y	US,A, 4,926,436 (Lo) 15 May 1990	1-10 11,12
Y	WO,A, WO87/00681 (Lo) 29 January 1987	1-12
Y	US,A, 4,995,699 (Lo) 26 February 1991	1-12
A	US,A, 5,051,582 (Bahns et al.) 24 September 1991	1-12
E,Y	US,A, 5,173,610 (Lo) 22 December 1992	1-12

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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03 MARCH 1993	19 APR 1993

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INTERNATIONAL SEARCH REPORT

International application No.
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Physical Review Letters, 16 April 1990 Scheidemann et al., pages 1899-1902.	10-12